

# Plasma and Beam Production Experiments with HYBRIS, a Microwave-assisted $\text{H}^-$ Ion Source<sup>\*</sup>

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**Abstract.** A two-stage ion source concept had been presented a few years ago, consisting of a proven  $\text{H}^-$  ion source and a 2.45-GHz Electron Cyclotron-Resonance (ECR) type ion source, here used as a plasma cathode. This paper describes the experimental development path pursued at Lawrence Berkeley National Laboratory, from the early concept to a working unit that produces plasma in both stages and creates a negative particle beam. Without cesiation applied to the second stage, the  $\text{H}^-$  fraction of this beam is very low, yielding 75 micro-amperes of extracted ion beam current at best. The apparent limitations of this approach and envisaged improvements are discussed.

**Keywords:** Negative hydrogen ion source, electron cyclotron resonance ion source

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## INTRODUCTION

Next-generation Proton Drivers that include an accumulator ring will have to rely on  $\text{H}^-$  ion sources with key performance parameters in the areas of beam current, duty factor, and time-between-services that exceed the present state-of-the-art by a wide margin. A novel concept for creating intense beams of negative hydrogen ion beams had been presented earlier on<sup>1</sup> with a description of the first steps towards its realization. In this ‘HYBRIS’ approach, an Electron Cyclotron Resonance (ECR) ion source<sup>2, 3</sup> operating at 2.45 GHz frequency is utilized as a primary plasma generator and coupled to an SNS-type multi-cusp  $\text{H}^-$  ion source.<sup>4, 5</sup> This secondary source utilizes the plasma electrons produced in the first stage and is driven by pulsed d. c., rather than rf, power in a cold-cathode configuration, thus avoiding the use of filaments which are the cause for the short lifetimes of conventional  $\text{H}^-$  sources or of an internal rf antenna that is a performance-limiting element in the present version of the SNS ion source. Initial tests were performed to assess two aspects of this approach: 1), to check the functionality of the available SNS ion source, the so-called startup source that is identical to the delivered SNS production units in all major technical details, driven by 2-MHz rf power as usual; and 2), to measure the maximum intensity of an electron beam that could be extracted from the ECR plasma generator operated in c. w. mode.

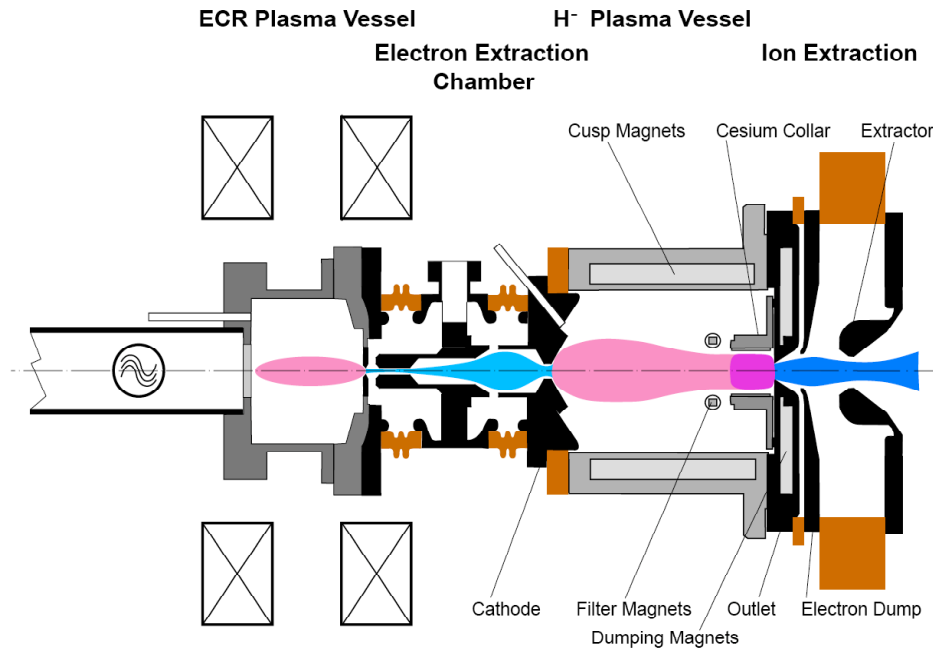
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In the second phase, the two plasma generators were attached to each other, starting with an attempt to create an electron beam and decelerate it upon injection into the  $H^-$  plasma vessel, and then modifying the configuration on the base of experimental findings. This phase ended in a closely coupled system where the outlet electrode of the ECR chamber was identical to the cathode of the  $H^-$  chamber. The last phase dealt with improving the negative-ion detection system and performing plasma density measurements in the multi-cusp chamber.

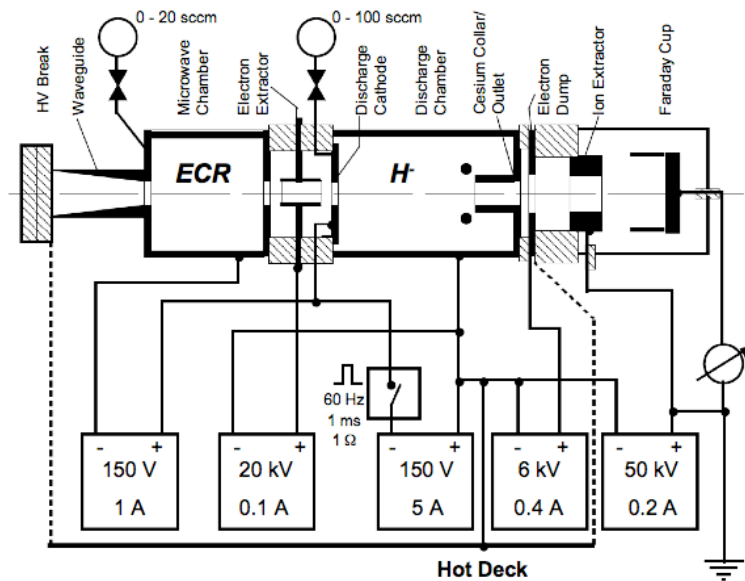
## EARLY EXPERIMENTS

The performance verification test of the SNS ‘start-up source’<sup>4</sup> driven by 45 kW of 2-MHz rf power but without cesium activation gave a positive result, with a measured ion current value of 15 mA. With a cesiated collar, three times more  $H^-$  beam current had routinely been generated during the earlier SNS tests. In the initial HYBRIS configuration, see Figures 1 and 2, electron beams of up to 1.5 A current were extracted from the ECR chamber at 5 kV extraction voltage and decelerated to about 100-eV energy upon injection into the  $H^-$  discharge chamber. The attempt to strike a discharge in the multi-cusp chamber, however, failed because the gas pressure in this chamber was too low, and when more hydrogen gas was fed directly into this second chamber to raise the pressure there, a discharge was struck, instead, in the electron extraction gap near the ECR chamber, and the electron beam could not be accelerated at all under these conditions.



**FIGURE 1.** Schematic of HYBRIS in its initial configuration.

Therefore the configuration was changed, eliminating the elaborate electron extraction system entirely and positioning the ECR outlet aperture a few mm upstream of the cold-cathode aperture. After several attempts, a weak discharge could finally be struck in the multi-cusp chamber when the ECR chamber was held on the same potential as the cold cathode.

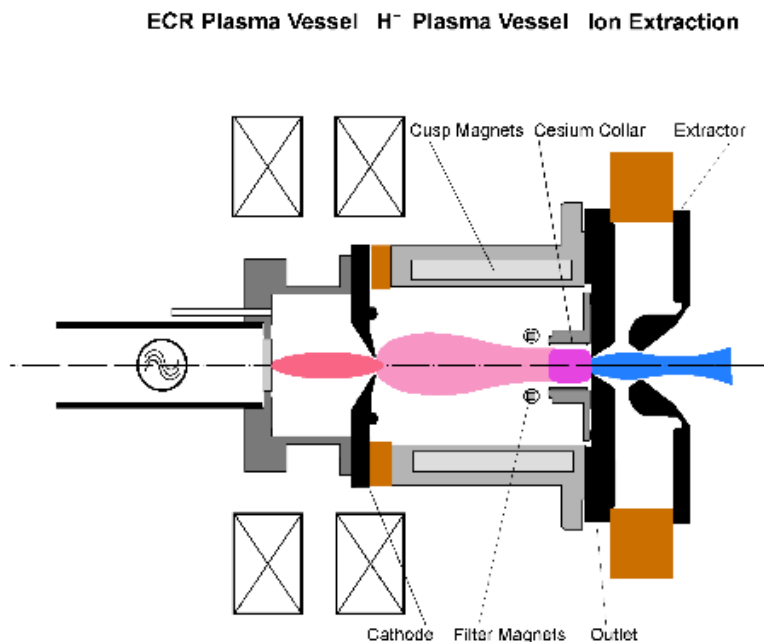


**FIGURE 2.** Electrical circuit of HYBRIS in its first configuration. Voltages and currents given represent the nominal values; operational values were actually lower than those.

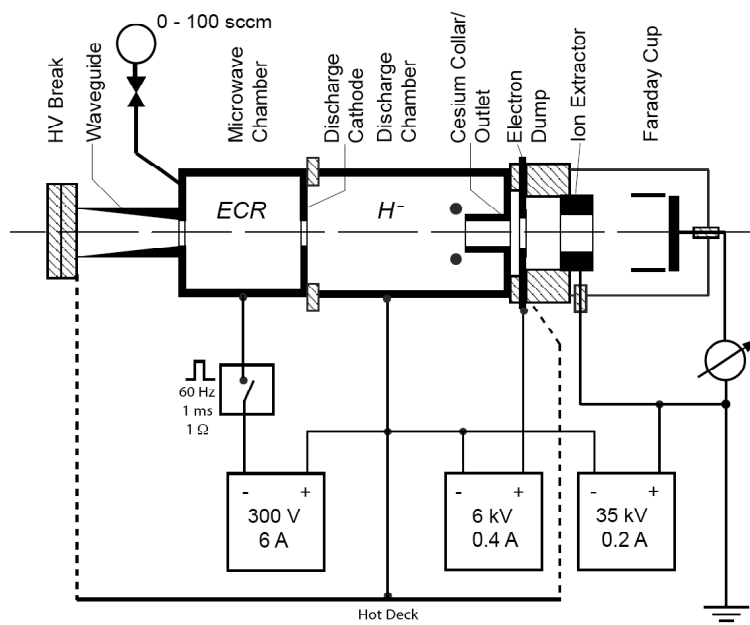
## IMPROVED SOURCE CONFIGURATION

In the most recent configuration, the ECR chamber is directly coupled to the multi-cusp chamber, with the ECR outlet flange being replaced by the cold cathode itself, see Figures 3 and 4. Electrons are now transferred to the multi-cusp chamber by ambipolar diffusion, and in this configuration, a discharge in the multi-cusp chamber can be readily ignited.

The price for achieving the cold-cathode discharge ignition lies in the reduction of system versatility: With the formerly used electron beam extraction system the energy of the electrons injected into the multi-cusp chamber could in principle have been adjusted to arbitrary values. With this option lost, primary electrons might have to be damped down in the main discharge itself if their initial energy upon injection were found incompatible with high survival rates of  $H^+$  ions produced inside the cesium collar. This damping effect could be achieved by extending the length of the multi-cusp chamber, thus enhancing the collision rates between primary electrons and cold particles. No such effort was actually undertaken during the last experiments reported here.



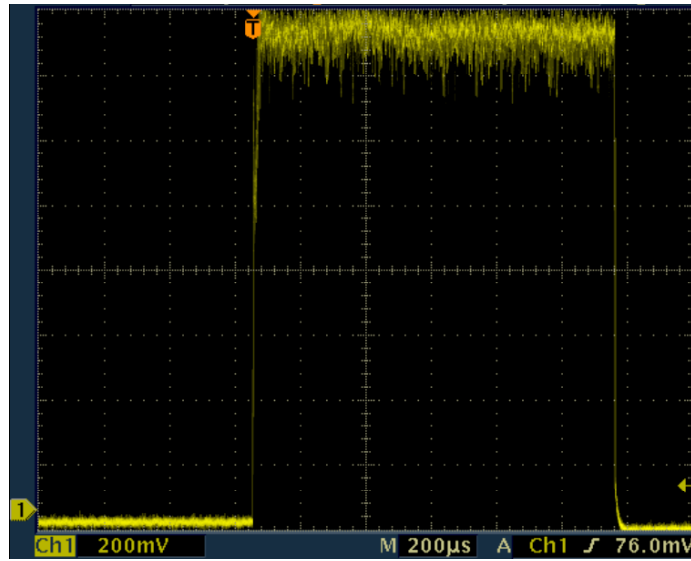
**FIGURE 3.** Schematic of HYBRIS in its most recent configuration.



**FIGURE 4.** Electrical circuit of HYBRIS in its most recent configuration. Voltages and currents given represent the nominal values; operational values were actually lower than those.

As a major result with the improved HYBRIS configuration, a discharge current of up to 17.5 A could be generated in the multi-cusp chamber with the forward microwave power at the maximum amplitude of 1.9 kW, a gas flow of 35 sccm, and 150 V effective discharge voltage. The reflected microwave power, however, amounted to

450 W under these conditions, indicating that the plasma density in the ECR chamber had reached the cut-off level at 1.45 kW and additional forward power was just getting reflected. An example of a slightly lower discharge current pulse is shown in Fig. 5. Extension of the flat discharge pulse for a duration of 2 ms at less than 6% duty factor was demonstrated as well. The axial magnetic field strength on the ECR chamber axis marginally exceeded the resonance level of 845 G over the entire length of the chamber, with the implication that exact resonance conditions are achieved on the surface of an elongated, ellipsoid-like, volume that intersects the dielectric window upstream on a narrow circle.

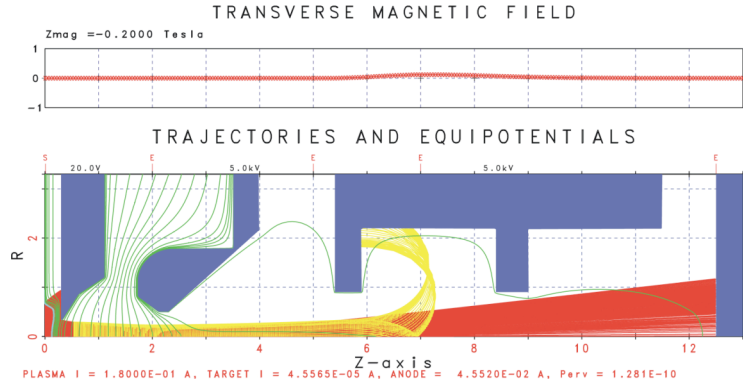


**FIGURE 5.** Demonstration of a 15.2-A discharge pulse with 1.1 ms duration at 6.6% duty factor, in the multi-cusp chamber of HYBRIS.

The first, very brief, attempt of extracting a beam of negative particles from the  $H^-$  plasma vessel did not result in observing any  $H^-$  ions in the presence of 8 mA electron current. Due to significant noise on the current signal, the measurement resolution for the ion current during this test was about 0.5 mA. To investigate the reason for the observed, unexpectedly poor, performance and possibly arrive at design improvements, the geometry of the two-chamber Faraday cup was revised, and the discharge was examined with a Langmuir probe.

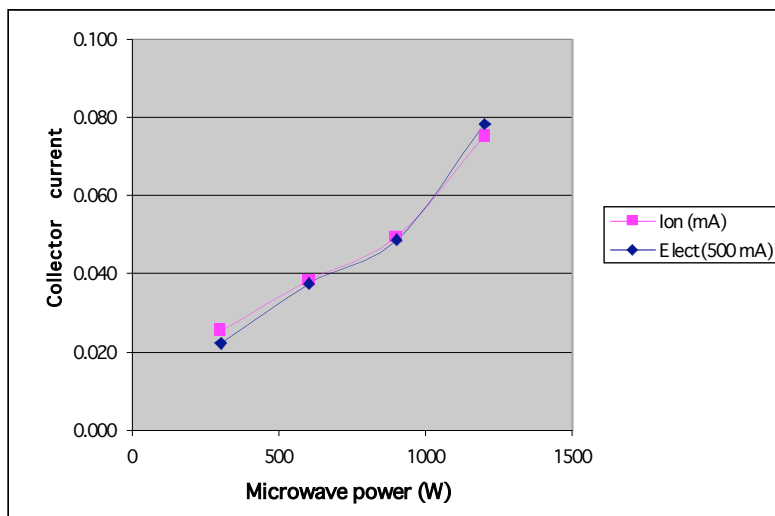
## FINAL RESULTS

The two-chamber Faraday cup used in all negative-particle beam measurements was rebuilt on the base of trajectory simulations with the code PBGuns.<sup>6</sup> Figure 6 shows a simulation representing the optimized layout. The complete separation of electrons and negative ions in this cup was demonstrated experimentally as well, by operating the source with helium that does not form negative ions.



**FIGURE 6.** PBGuNS simulation of the extraction diode and the two-chamber Faraday cup at a beam energy of 5 keV.

The Langmuir probe measurements showed that the current density in the multi-cusp chamber only reached values of  $20 \text{ mA/cm}^2$  at 1 kW forward power, whereas densities of  $200 - 300 \text{ mA/cm}^2$  have been measured in 2.45-GHz ECR ion sources. It was also observed that striking a discharge in the multi-cusp chamber perturbs the ECR discharge itself, making impedance matching harder to achieve. The  $\text{H}^-$  and electron beam current values obtained at 200 V discharge current in the multi-cusp chamber are displayed in Figure 7. The results show that the electron/ion current ratio is rather constant and, with a value of about 500/1, very high even considering that the collar was not cesiated. Another finding was that the ion density in the multi-cusp chamber increased with rising discharge voltage, but values above 200 V are considered impractical because the average electron energy would rise too much for  $\text{H}^-$  ions to survive.



**FIGURE 7.**  $\text{H}^-$  and electron beam currents at voltages of 200 V (discharge) and 10 kV (extraction).

## OUTLOOK

Based on all experimental evidence gathered so far we have to conclude that the fundamental idea of combining an ECR discharge with a cold-cathode discharge is meeting with considerable difficulties and has only slim chances for actually succeeding. The main problems appear to be the insufficient plasma density achieved in the multi-cusp chamber and excessive primary electron energies originating from the ECR discharge. The experiences gained, however, have led to a new attempt of developing a hybrid  $H^-$  ion source where a helicon plasma device is being used instead of a 2.45-GHz ECR discharge.<sup>7</sup>

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